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13. ABSTRACT (Maximum 200 words)

This project concerns the exploration of two novel and enabling technologies: a self-collimated multi-wavelength laser (SCMWL), and the underlying binary supergrating (BSG), on which the SCMWL depends. In this context, the BSG functions as a multi-wavelength reflector which can be implemented by a simple two-level etching process. The SCMWL makes use of BSGs to form a planar cavity with collimated multi-wavelength resonances. When combined with gain, the result is self-collimated multi-wavelength output.

This project began at the University of Toronto, under grant number DAAG55-98-1-0435, where it was demonstrated for the first time that both the BSG and the SCMWL concept work, through implementations in an optically-pumped AlGaAs planar waveguide. After Year 1 of this 2-year project, Professor Xu's lab relocated to Brown University, where work on this project has continued. Here we report on this second year of exploration, in which we have extended and solidified our understanding of SCMWL operation, and developed a measurement methodology for these novel devices. This provides a firm foundation for the next phase of SCMWL development, including electrically-pumped implementations promising greater efficiency and output power.

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Final Progress Report

Binary Super Grating (BSG) self-collimated multi-wavelength laser
Principal Investigator: **J.M. (Jimmy) Xu**

ARO Proposal Number: P-40440-EL Grant Number: DAAD19-00-1-0003

FOREWORD

This project concerns the exploration of two novel and enabling technologies: a self-collimated multi-wavelength laser (SCMWL), and the underlying binary supergrating (BSG), on which the SCMWL depends. In this context, the BSG functions as a multi-wavelength reflector which can be implemented by a simple two-level etching process. The SCMWL makes use of BSGs to form a planar cavity with collimated multi-wavelength resonances. When combined with gain, the result is self-collimated multi-wavelength output.

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Statement of the Problem Studied

The objective of this project was to build on the success of our Year 1 exploration, in which we designed and fabricated the first proof-of-concept implementation of a novel self-collimated multi-wavelength laser (SCMWL), enabled by the novel binary supergrating (BSG), also developed by Xu's group. The BSG can be described as a sampled sequence of equal-width lines whose effective index is one of two values. The determination of this binary pattern, which can be represented as a sequence of 1's and 0's, lies at the heart of BSG synthesis. This concept can be applied in any waveguide structure, independent of material, and can produce nearly arbitrary diffraction characteristics. When combined with gain, BSGs can become feedback elements for multiwavelength lasers (MWLs).

MWLs have great potential in a variety of applications, enabling the increased transmission rates of wavelength-division multiplexing (WDM) systems, and enhanced operation in free-space settings such as range-finding, beam guidance, and infra-red counter-measures (IRCM). Ideally, MWLs should have low inter-channel interference (crosstalk), high power, low beam divergence for optimum coupling or free-space propagation, and be compact. In addition, it is highly desirable that any associated tuning circuitry be as simple as possible for ease of packaging and control.

No MWL achieves all these ideals, and in fact all previous MWL designs suffer from high divergence. The ideals of high power and low divergence are generally in contradiction due to the requirement of single-lateral-mode operation, which for existing MWLs restricts both current density and beam width. To overcome this, a design is required which simultaneously permits broad-beam collimation and monomode operation, with simultaneous emission of multiple wavelengths.

This can be achieved by exploiting the freedom afforded by planar propagation, by implementing BSGs in a planar waveguide to define a two-dimensional ring cavity as shown in Figure 1. When combined with gain, this leads to simultaneous multi-wavelength lasing, where the gratings define not only peak wavelengths but also beam divergence, leading to the attractive properties of self-maintained wavelength spacing (i.e. no drift-induced cross-talk) and self-collimation.

The operation of this device can be understood by first considering the diffraction characteristics of BSG-A in Figure 1, whose M diffraction wavelengths depend on incident angle θ according to:

$$\lambda_m(\theta) = 2\, n_{eff} \Lambda_m \cos(\theta), \tag{1}$$

where Λ_m represents the emulated grating pitches and n_{eff} is the effective modal index. The N diffraction wavelengths of BSG-B depend similarly on $\phi = \theta - 90°$. The ring cavity design thus constrains resonances to wavelength/angle pairs which are simultaneously diffracted by BSGs A and B, as shown graphically in

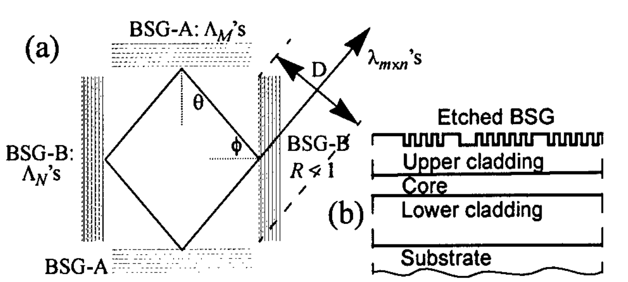

Figure 1. Schematic of SCMWL implementation: (a) top-view of structure with two twin BSGs; and (b) side view of etched-BSG implementation. Indicated paths correspond to peak of beam, which in fact fills most of inter-grating area.

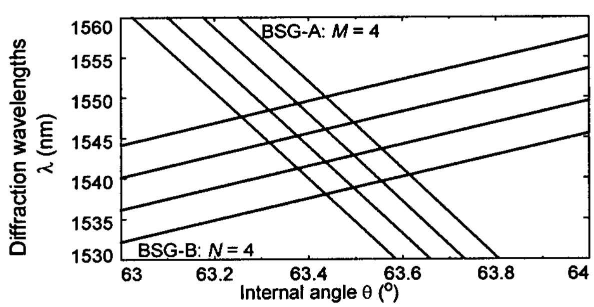

Figure 2. Diffraction wavelengths vs. internal angle for BSGs of a SCMWL. In this example, intersections correspond to 16 resonant wavelengths spaced by 0.8 nm in the 1.55 μm region.

Figure 2. The result is a self-collimated comb of $M \times N$ wavelengths with self-maintained spacing: fixing the entire comb requires feedback monitoring of only a single channel.

In Year 1, we obtained the first experimental evidence corroborating the novel concepts of the self-collimated multi-wavelength laser and the binary supergrating, through an optically-pumped implementation in an AlGaAs planar waveguide. In the second year of this on-going and open-ended exploration, we have extended and solidified our understanding of the operation of these novel devices, both theoretically and experimentally, and have established a suite of design tools and test apparatus for soon-to-come electrically-pumped SCMWLs.

SUMMARY OF MOST IMPORTANT RESULTS

The number of resonant wavelengths supported by the SCMWL is given by MxN, where M and N are the number of pitches emulated by each grating pair. In our Year 1 explorations, first-cycle devices with M and N equal to 1 or 2 were developed, with three combinations of MxN: 1x1 (single peak); 1x2 (2 peaks spaced by 6 nm); and 2x2 (2 interlaced pairs of peaks spaced by 6 nm). When pumped optically, these devices emitted the expected number of wavelengths, but with one unexpected result for the 2x2 device: there was a slight asymmetry in the interlacing, resulting in uneven peak spacing, as shown in Figure 3.

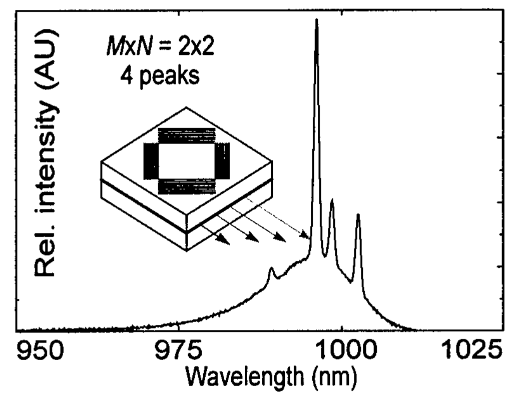

Figure 3. Spectrum observed from optically-pumped first-cycle device, showing four peaks whose spacing is close to, but not exactly, that expected.

Further investigation revealed that the output was not purely TE or TM, as expected, but was rather of mixed polarization, suggesting a coupling between TE and TM modes, which would indeed skew the originally-expected peak spacing. TE-TM coupling is a known phenomenon associated with grating reflections in the neighbourhood of 45°, as was the case here (internal angles θ and ϕ of 54.7° and 35.3° respectively).

In cases where pure polarization output is desired (typically TE), polarization coupling should be avoided. This can be accomplished by employing a cavity with a more extreme aspect ratio (which corresponds also to the ratio of the pitches emulated by BSG-A and -B), whose internal angles lie further from 45°. For such configurations, resonant modes will be pure TE or pure TM, and not a hybrid of these.

This design difference lies at the heart of the second-cycle designs, whose internal angles θ and ϕ lie in the neighbourhood of 70° and 20° respectively (corresponding to a cavity aspect ratio of tan(70°) ~ 2.75). M and N were chosen to have values of 1, 2, or 4, with the objective of yielding as many as 16 (i.e. 4x4) wavelengths. In particular, BSG-A emulated M pitches in the vicinity of 420 nm (ranging from 406.8 to 428.9 nm), whereas BSG-B emulated N pitches in the vicinity of 150 nm (ranging from 149.9 nm and 154.1 nm). With the modal index n_{eff} of ~3.44, this yields expected peaks in the region of 980 nm, within the gain spectrum of 20% InGaAs quantum wells located in the core of the AlGaAs planar waveguide employed.

Figure 4 shows the waveguide cross-section, and a top-view schematic of the second-cycle SCMWLs. Binary supergratings (BSGs) were fabricated in an AlGaAs planar waveguide via electron-beam lithography followed by reactive ion etching, producing etch depths between 100 and 150 nm.

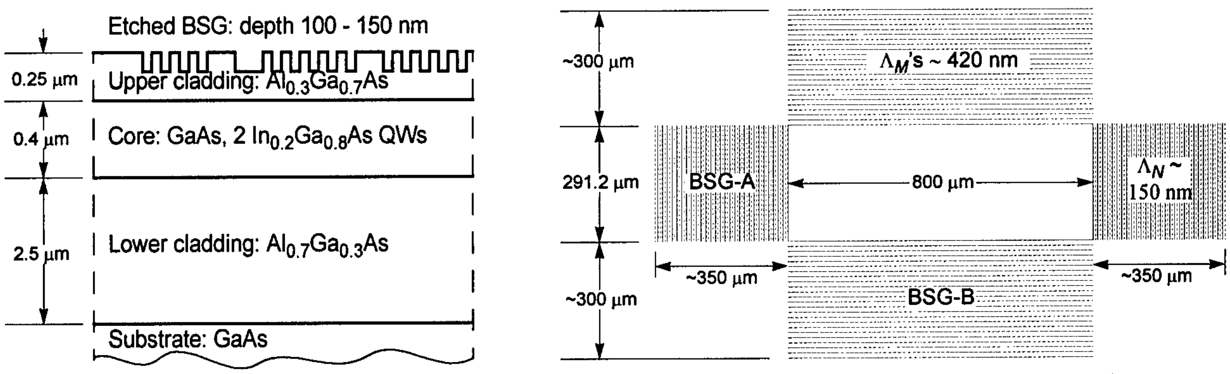

Figure 4. *Left:* Cross-section of AlGaAs planar waveguide, with modal index ~3.44 and gain peaked at 980 nm from InGaAs QWs. *Right:* Top-view design of second-cycle SCMWLs.

The SCMWLs were then pumped at normal incidence using ~50 ns optical pulses, emitted by an Q-switched alexandrite laser, with a wavelength of 755 nm and a maximum peak power density of ~100 W/ mm^2. It should noted up front that optical pumping is patently not as efficient as electrical pumping, and that with designs informed by our present exploration the latter offers far greater efficiency and output power. However, our chosen approach offers the advantage of eliminating any extraneous complications such as faulty contacts, and focuses on the essential question of whether or not SCMWLs actually work.

The edge-emitted output from the SCMWLs was focussed to a monochromator, and the resulting spectrum measured. One of our first tasks was to verify whether the observed peaks, which due to heating effects and setup limitations are somewhat broadened, in fact correspond to lasing. This was confirmed by the threshold behaviour of output power vs. input peak power, shown in Figure 5. Beyond an average-pump-power threshold of 0.11 mW, output power increases linearly, as expected for lasing. With the pump beam diameter of 2 mm and pulse-width of 50 ns, this yields a threshold peak power density of 18 W/mm^2, which represents an improvement over the first-cycle devices, for which the threshold was ~100 W/mm^2.

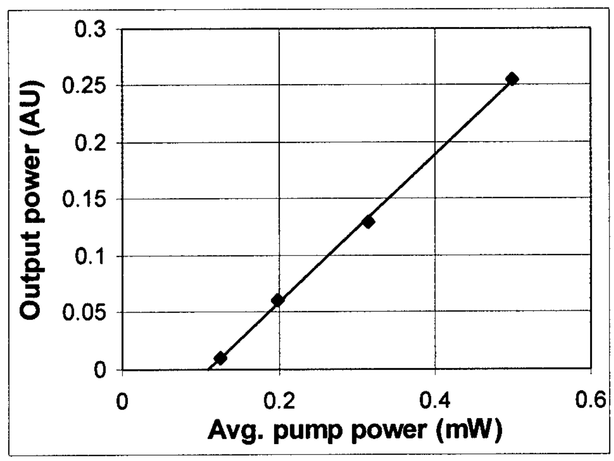

Figure 5. Threshold behaviour of observed peak for a 1x1 (single-wavelength) device, showing linear growth beyond an average pump power of 0.11 mW. This corresponds to a threshold peak power density of 18 W/mm^2.

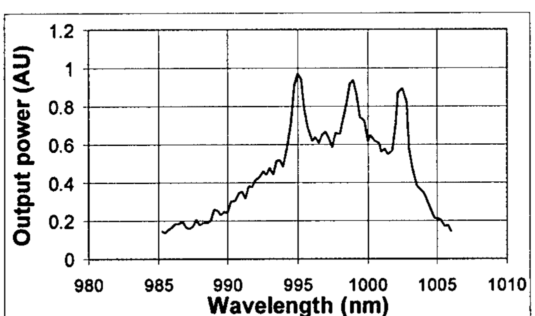

Figure 6. Output spectrum for 1x4 SCMWL. Strong ASE background is an expected consequence of optical pumping, and the red-shift is due to heating effects.

Figure 6 shows the spectrum observed for a 1x4 SCMWL, showing 3 evenly-spaced peaks with comparable output powers. The missing fourth peak lies in the fringes of the gain spectrum, and The large amplified spontaneous emission (ASE) background, familiar from our first-cycle designs, is an expected and inevitable consequence of optically pumping material outside the cavity region. The shift to wavelengths longer than predicted is due to heating and the plasma effect (i.e. high carrier densities). The observed linewidths are broadened by two limitations of our present setup: an effective resolution of ~0.25 nm; and heating effects. Nevertheless, the experimental results of Figure 6 are a compelling confirmation of the SCMWL concept, and furthermore represent the first demonstration of 3 balanced and evenly-spaced output peaks from an SCMWL.

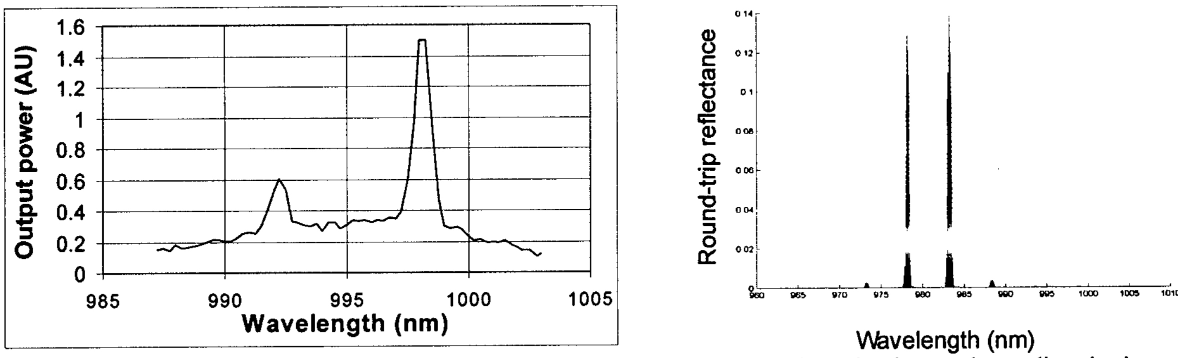

Figure 7. *Left:* Output for 1x2 SCMWL, showing peaks with expected spacing but moderate disparity in strength. *Right:* Simulated round-trip reflectance.

We have also developed a simulation tool to compute round-trip reflectance as a function of internal angle (θ) and wavelength, which takes into account both waveguide and material dispersion. Ideally, round-trip reflectance should compensate for disparities in round-trip gain, which is a critical parameter requiring experimental extraction. Figure 7 shows experimental data for the 1x2 SCMWL, alongside its simulated round-trip reflectance (note that this is not the predicted output spectrum per se, whose computation must include wavelength-dependent gain), showing excellent agreement with regards to peak spacing. As can be seen, the disparity in peak height correlates to a disparity in round-trip reflectance, which is an unexpected (but now understood) characteristic of SCMWLs, with roots in a subtlety of oblique-incidence Bragg diffraction, and in the material properties of our AlGaAs waveguide.

Through the combined effects of material and waveguide dispersion for our AlGaAs waveguide, it turns out that all with else being equal, longer wavelengths will have stronger reflectance feedback. This can be seen from Figure 6, which plots index modulation vs. wavelength for a variety of grating etch-depths. Index modulation relates to a grating's coupling strength, and hence the strength of feedback, so that without compensation longer resonant wavelengths will have a larger round-trip reflectance. Fortunately, this (and any other) disparity can easily be corrected through judicious BSG design; however, one should also account for the aforementioned subtlety of Bragg diffraction.

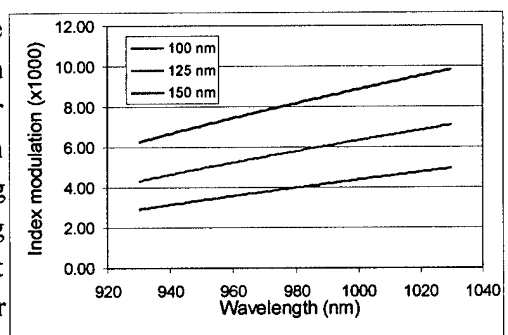

Figure 6. Index modulation vs. wavelength, for grating etch-depths of 100 nm (lower curve), 125 nm (middle), and 150 nm (upper). Longer wavelengths have larger modulation, which if uncompensated yields larger round-trip reflectance.

This subtlety is revealed with the simulated round-trip reflectance for the 4x4 SCMWL, which as shown in Figure 9 has resonances at 16 evenly-spaced wavelengths. As can be seen from the 2D plot of reflectance vs. wavelength, there is a clear pattern in the relative peak heights. The overall trend of peak reflectance increasing with wavelength is a consequence of the above-described index modulation dispersion. For insight into the sub-trend of increasing reflectance within each set of four peaks, one may consider the top-view plot showing internal angle, which reveals that larger oblique angles of incidence yield higher reflectance, as characteristic of Bragg diffraction.

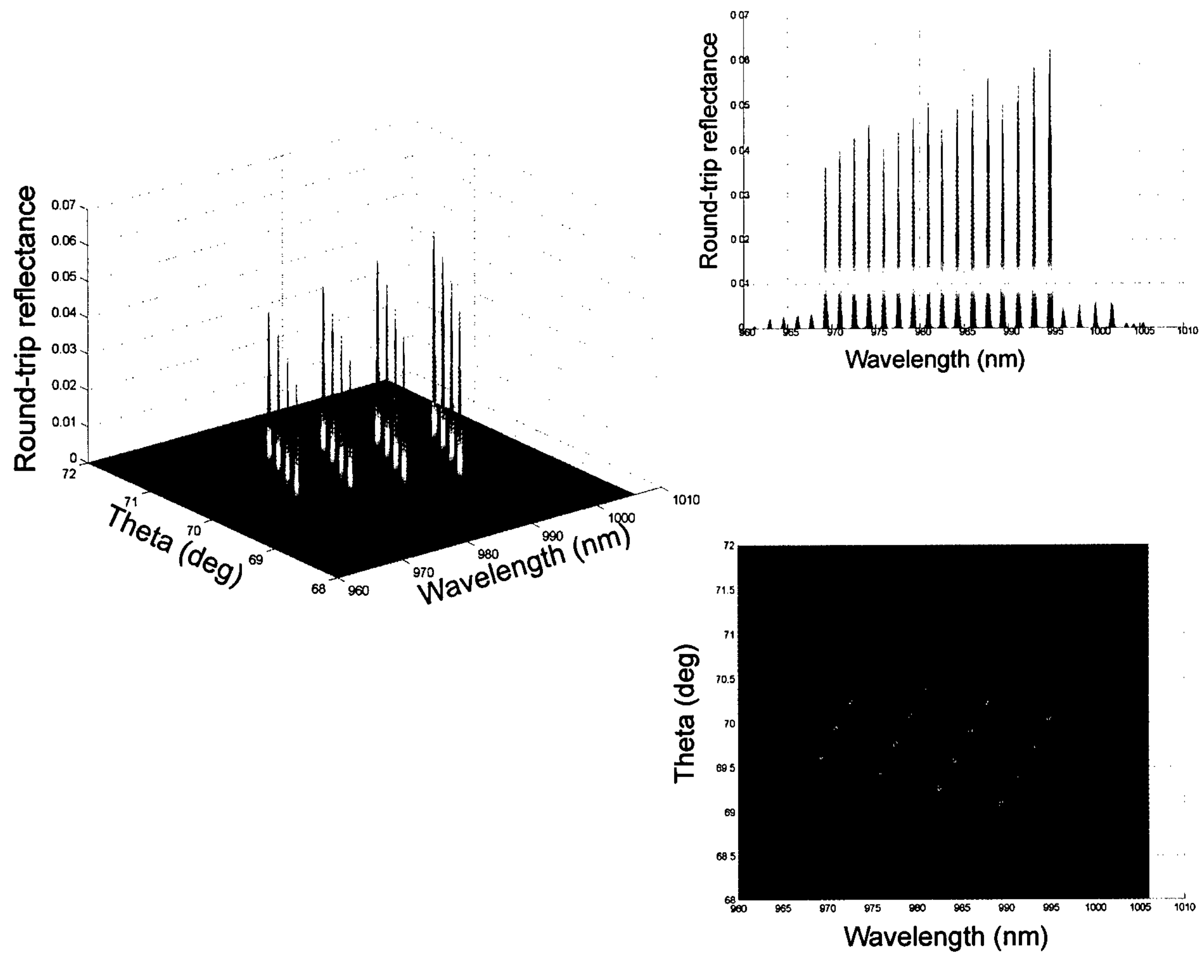

Figure 8. Simulated round-trip reflectance for 4x4 SCMWL, with different views showing 3D plot (upper left); comparative peaks heights (upper right), and top-view mapping of angle-wavelength pairs (bottom). Two trends can be observed: round-trip reflectance tends to be higher for (a) larger wavelengths; and (b) larger oblique internal angles. Such disparities, along with any others, can be easily compensated through an appropriate adjustment of the relative strength of the pitches emulated by the BSGs.

Fortunately, the aggregate spectral disparity from the combined effects of index modulation dispersion, diffraction efficiency, and gain can be easily be accommodated through an inverse weighting of the corresponding pitches emulated by the BSGs. For these second-cycle devices, no such correction was implemented, but the simulation tools developed for this project will form a valuable basis for future designs.

It should be said that the preliminary results presented here are restricted by the available apparatus and the optical pumping scheme, and by no means represent the performance limit of the SCMWLs. Of far greater importance is the fact that the stage is now set for the design of truly high-performance electrically-pumped implementations, with optimized heat removal, efficiency, and output power; and with promised application in both civilian and military applications. The SCMWL represents an entirely new lasing technology, and as such has required an entirely new measurement methodology, and here too lies the lasting and on-going value of this project: developing the required experimental apparatus has been a technical achievement in itself, and assures both a continuation of this open-ended exploration and value well beyond this project.

List of Manuscripts

In addition to publications from the official period of coverage of this grant, this list also includes publications during an administrative delay (due to the move from the University of Toronto to Brown University), between the end of the first year of funding (July 1, 1999), and the start of the second year of funding (Nov. 15, 2000).

M. Fay, P. Mathieu, A.J. SpringThorpe, J.M. Xu, "Self-collimated multiwavelength laser enabled by the binary superimposed grating: Concept, design, theory, and proof-of-principle experiment", *LEOS '99* - San Francisco, CA, November 8-12, 2000, Paper TuY4.

J.M. Xu, "Binary Super Gratings and Self-Collimated Multi-Color Laser", *NASA JPL Seminar*, August 12, 1999, Pasadena, CA.

J.M. Xu, "Self-Collimated Multiple Wavelength Laser enabled by Binary SuperGratings", *DARPA Optoelectronics Review*, August 1-4, 1999, San Diego, CA.

J.M. Xu, "Binary Super Gratings -- A new enabling technology for WDM", *SPIE International Symposium on Optical Science, Engineering, and Instrumentiation*, July 18-23, 1999, Denver, CO.

J.M. Xu, "Bianary Super Gratings -- A new enabling concept for WDM optics", Aoyama Gakuin University, Tokyo, Japan, March 7, 2000.

J.M. Xu, "Binary Supergratings -- an enabling WDM technology", Institute of Fiber Optics, Shanghai, China, June 11-14, 2000.

Martin Fay, Hope Chik, J.M. Xu, "Two new enabling technologies for WDM and Integration: Binary SuperGratings and Lateral Current Injection Lasers", invited seminar, Corning R&D, Boston, March 9, 2001.

Participating Scientific Personnel

Prof. J.M. Xu - Principal Investigator
Martin Fay - PhD student
Hope Chik - PhD student
Tom Kucera - Undergraduate student

Report of Inventions

(No new inventions to report.)